

Oceanographic and Meteorological Aspects of the Gulf of California¹

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THE PRIMARY OBJECT of the present paper is to give an adequate description of the climatic and oceanographic conditions in the Gulf as they are known today.

Only a few authors have discussed the Gulf (Sverdrup, 1940; Osorio Tafall, 1944) and only the geological work was described in detail (Anderson, 1950; Durham, 1950; Natland, 1950; Revelle, 1950; Shephard, 1950).

The data used in the present investigation are largely taken from the "E. W. Scripps" expeditions in 1939 (Sverdrup and staff, 1943) and from the publications of the Servicio Meteorológico Mexicano, the U. S. Coast and Geodetic Survey, and the U. S. Hydrographic Office.

The data for the Gulf are few and the conclusions that can be drawn from them are necessarily limited and should be taken only as a first approximation until more and better data are at hand.

The Gulf of California is of considerable interest both scientifically and economically,

and it is expected that its importance will steadily increase in the future, especially as an additional food source for Mexico. A thorough knowledge of the physical and chemical changes taking place in the Gulf is essential to the understanding of its fisheries.

Moreover, the Gulf is interesting because it represents the only large evaporation basin of the Pacific Ocean and because it shows certain differences from other comparable evaporation basins. A final answer to all the different problems in the Gulf cannot be expected from the meager data available but it is the hope of the author that this paper may stimulate more research in this intriguing area.

ACKNOWLEDGEMENTS

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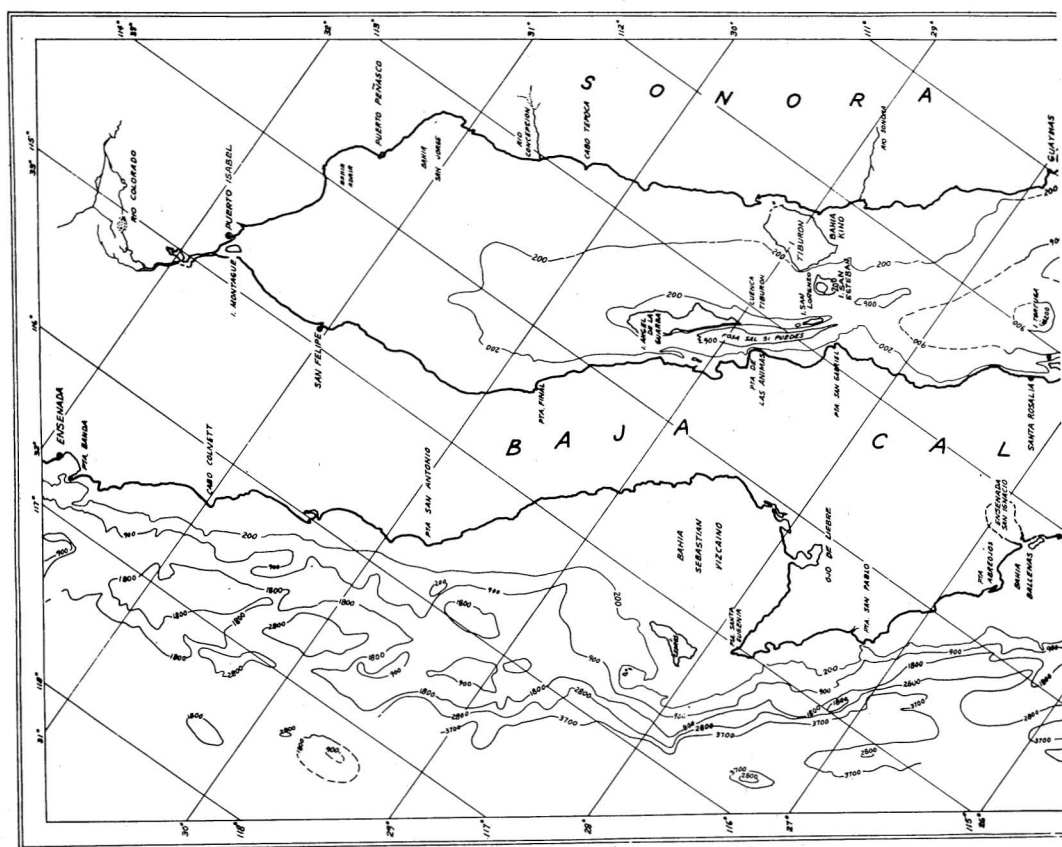


FIG. 1. Bathymetric map of the Gulf of California.

GENERAL DESCRIPTION AND PREVIOUS INVESTIGATIONS

The Gulf of California is unique in many respects. Lying as it does in a predominantly arid region it comprises the only large evaporation basin of the Pacific Ocean. It is roughly rectangular in shape and lies between the Mexican states of Baja California to the west and of Sonora and Sinaloa to the east. At its southern end the Gulf is in open communication with the ocean. The length of the Gulf is about 1400 km. and the average width about 150 km., giving a total surface area of roughly 210,000 km.², if the southern boundary is taken along latitude 23°N. Between this latitude and a line joining Cabo San Lucas with Cabo Corrientes (Fig. 10) lies a transition region which occasionally is in-

fluenced by Gulf water (Schott, 1935). This region will be called the Gulf Entrance, and it has a total surface area of roughly 40,000 km.²

Topographically the Gulf can be divided into a number of basins, separated from each other by transverse ridges. The deepest basins have a maximum depth of more than 3000 m. and a sill depth below 1500 m. (Geol. Soc. Amer., Mem., 1950). In the northern part of the Gulf isolated basins are found in which different hydrographic conditions prevail (Sverdrup, 1941). These basins seem to represent deep depressions in an otherwise quite narrow shelf and are completely isolated below 200 to 300 m. Their isolated character is quite sufficient to explain the hydrographic conditions found in them and it is not neces-

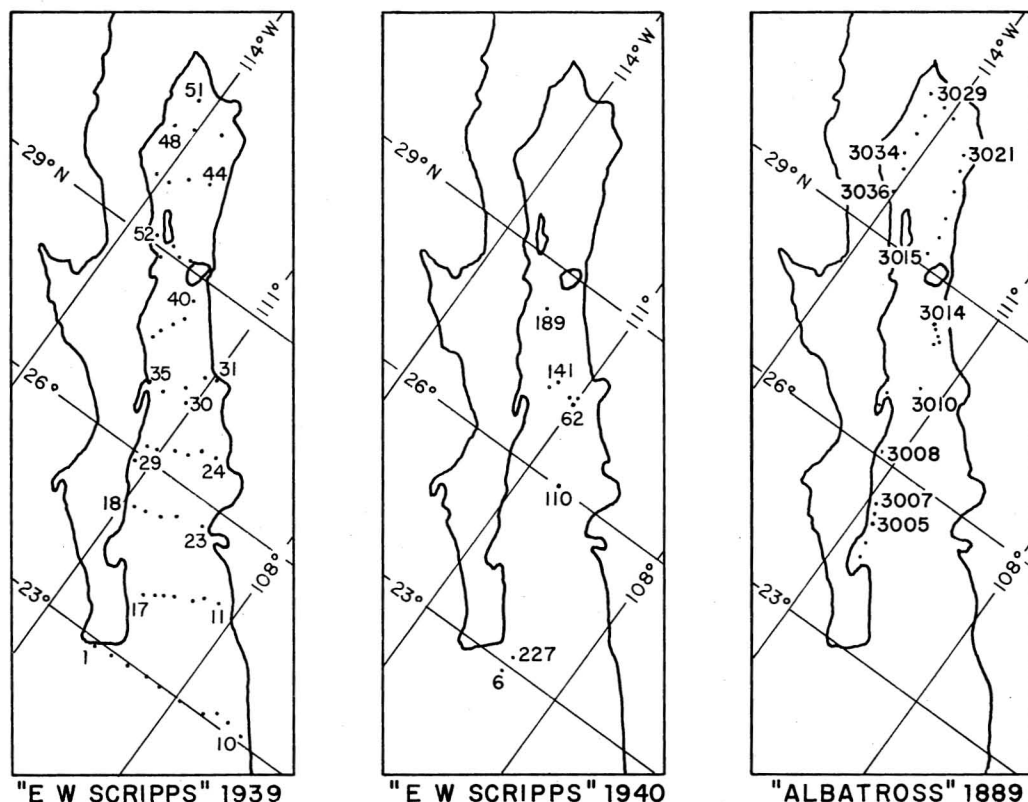


FIG. 2. Stations occupied on previous expeditions.

Considerable warming and high salinity were found in shallow bays such as Bahia Guaymas and Bahia Concepcion. Upwelling was characteristic along the northern coast of Sonora where the temperature was about one degree lower and the salinity 0.4‰ lower than in the neighborhood offshore. Near the mouth of Rio Colorado the salinity varied between 35.2 and 35.7‰ , probably due to the admixture of fresh water. The bottom temperatures in the northern part everywhere exceeded 11°C . and the bottom salinity varied between 35.5 and 36.1‰ .

The next important description of the Gulf of California was made by Thorade (1909) in a paper on the California Current. He examined a great number of ship logs over many years and was the first investigator to draw monthly surface temperature charts (Fig. 4)

for the southern part of the Gulf and deduce from them the general circulation in the Gulf and to correlate the sea surface temperatures to the direction of the wind, the orientation of the shore line, and the special climatological conditions prevailing in the Gulf. His main conclusions were that the temperature of the Gulf is independent of the temperature in the adjacent ocean and that the low temperatures along the east coast in winter are the result of northerly winds that tend to transport surface water away from the coast and thus produce upwelling. He also observed correctly that during most of the year the circulation is counterclockwise in the Gulf and that the water enters the Gulf along the east coast and leaves it along the west coast. He mentioned that "manifold discontinuities are observed by a sudden change in tem-

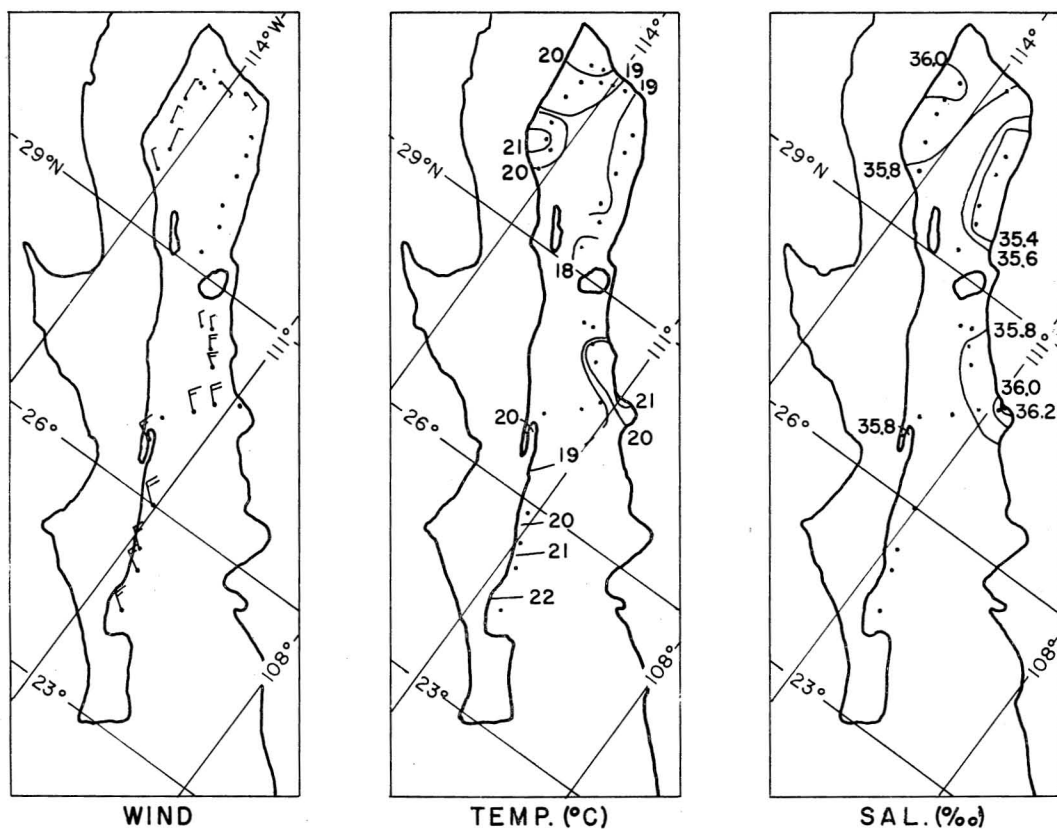


FIG. 3. Distribution of winds, temperature, and salinity in March, 1889.

perature" in the vicinity of Cabo San Lucas, which might well have been the first description of the San Lucas front.

Schott (1935: 208) described the Gulf of California as part of the Mexican region, a region defined roughly as lying between the Gulf of Tehuantepec and Cabo San Lucas and extending seaward between the California Current and the North Equatorial Current. The Mexican region is characterized by a very high surface temperature and very weak circulation. He briefly mentioned the temperature discontinuity near Cabo San Lucas and drew attention to the frequent hurricanes in that region.

In the spring of 1939 the Scripps Institution of Oceanography sent an expedition into the Gulf led by H. U. Sverdrup on the "E. W. Scripps." Fifty-three stations were made in the

Gulf (Fig. 2) taking temperature, salinity, oxygen, calcium carbonate and plankton observations on each station from the surface to the bottom (Sverdrup and staff, 1943). These data are still the most complete ever taken in the Gulf. Sverdrup's main conclusions were that the Gulf can be subdivided into two parts, a northern part and a southern part, separated from each other by a submarine ridge which comes to within 200 m. below the surface. The water mass to the north is largely of local origin and formed by convective currents in winter, the water to the south is nearly the same as in the adjacent ocean and only modified slightly at the surface by extensive evaporation (Sverdrup, 1941).

In late fall of 1940 the "E. W. Scripps" made a second trip to the Gulf. The chief

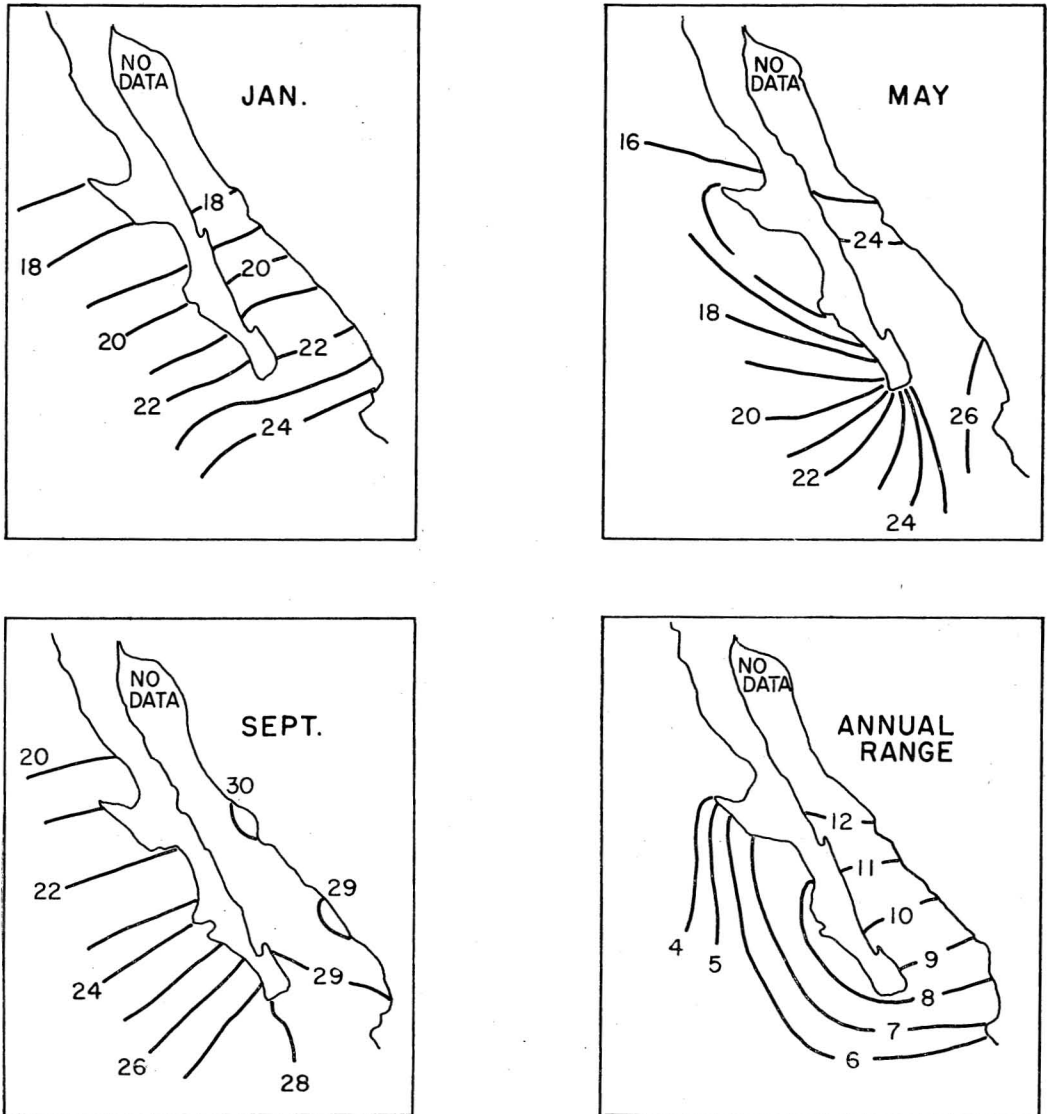


FIG. 4. Sea surface temperatures ($^{\circ}\text{C}.$) in the Gulf of California. (After Thorade, 1909.)

aim was geological (Geol. Soc. Amer., Mem., 1950) but a few hydrographic stations were made (Fig. 2). Silicate and phosphate were measured for the first time in the Gulf, but the methods used in determining the concentrations do not warrant a detailed description of them. A brief account on the silicate distribution in the Gulf was given by Sverdrup (Sverdrup and staff, 1940). In 1944 the Mexican government sponsored a brief study

of the Gulf in order to determine the feasibility of a minor guano industry (Osorio Tafall, 1944). The industry was never started. In 1956 the U. S. Fish and Wildlife Service has planned two expeditions into the Gulf to study the distribution of sardine eggs and larvae and to make frequent hydrographic stations, which undoubtedly will bring back new and valuable data for further scientific investigations.

CLIMATOLOGY

The great differences in climatic conditions observed in the Gulf as one proceeds from northwest to southeast, covering nearly nine degrees of latitude, and the differences that exist between the east side and the west side of the Gulf, are closely related to the atmospheric circulation and to the existence of mountain ranges that modify this circulation.

The influence of the Pacific Ocean upon the climate of the Gulf is greatly reduced by a nearly unbroken chain of mountains, 2000 to 3000 m. high, in Baja California. The considerable differences in temperatures and precipitation between the Pacific side and the Gulf side have already been mentioned by Thorade (1909) and are fully confirmed by data collected by the Servicio Meteorológico Mexicano (Boletín Anual). Along the Pacific side of the peninsula the air temperatures are never excessively high and precipitation falls during the winter season in the northern part, and during the summer season in the southern part, with annual amounts around 200 mm. Along the Gulf side air temperatures are very high in summer and rather cool in winter. In

the north all the precipitation falls in summer. The amount of rainfall (Table 1) varies between traces in the north and 200 mm. at the southern tip of Baja California, which is crossed by the Tropic of Cancer. The rainfall on the corresponding latitude on the eastern side of the Gulf amounts to 400 mm. per year.

On the average the west coast of the Gulf receives only half as much rain as the east coast. In Sonora the winter is cool and the summer hot. Precipitation falls from July to September, varying between traces in the northernmost part and 251 mm. in Guaymas. In Sinaloa the winter is warm and the summer less hot than in Sonora. Precipitation falls from August to October, with amounts between 300 mm. in the north and 850 mm. in Mazatlán (Table 1). From the discussion of the precipitation figures it becomes evident that the Gulf of California is far from being situated in a desertlike environment.² The vegetation in Baja California and Sonora is of

² Most Americans call northern Sonora and Baja California a desert, though people from North Africa and South America would consider this region a dry steppe.

TABLE 1
MEAN MONTHLY AIR TEMPERATURE AND PRECIPITATION 1921-1935 (SERV. MET. MEX., BOLETÍN ANUAL)

	WEST COAST (IN GULF)				EAST COAST (IN GULF)				EAST COAST (OUTSIDE GULF)			
	Mulege (26°53'N- 112°00'W)		La Paz (24°10'N- 110°18'W)		Guaymas (27°55'N- 110°53'W)		Topolobampo (25°36'N- 109°03'W)		Mazatlán (23°11'N- 106°25'W)		Cabo Corrientes (20°24'N- 105°43'W)	
	Temp.	Prec.	Temp.	Prec.	Temp.	Prec.	Temp.	Prec.	Temp.	Prec.	Temp.	Prec.
	°C.	mm.	°C.	mm.	°C.	mm.	°C.	mm.	°C.	mm.	°C.	mm.
January...	14.0	2.6	18.2	3.2	17.7	7.9	18.6	6.4	19.3	11.0	23.2	19.5
February..	16.0	3.4	19.2	11.4	18.9	6.3	19.7	6.6	19.4	9.7	22.9	29.6
March.....	17.8	0.1	21.3	0.8	20.7	4.6	20.1	6.4	19.7	3.4	22.7	1.3
April.....	20.1	0.2	23.2	0.2	22.8	3.0	22.2	tr.	21.3	0.1	23.9	tr.
May.....	22.9	0.1	25.5	tr.	25.5	2.8	25.0	1.8	23.8	1.8	25.4	2.3
June.....	27.2	tr.	27.2	0.2	28.8	0.7	29.1	5.3	26.4	29.2	26.7	57.3
July.....	30.5	6.1	30.0	6.3	30.7	46.7	29.8	39.9	27.5	166.9	28.9	145.0
August....	30.4	16.8	30.3	41.7	30.5	75.5	29.7	100.6	27.6	241.8	27.9	272.1
September.	29.0	40.0	29.0	51.9	30.2	54.4	29.7	55.9	27.5	268.6	27.5	307.0
October...	24.6	5.4	27.0	9.6	27.3	9.5	27.8	73.7	26.7	61.6	27.5	91.0
November.	19.5	6.8	23.2	13.4	22.6	11.1	24.0	7.0	23.5	11.7	26.1	15.2
December.	14.9	19.2	20.0	34.3	18.6	28.9	19.7	55.3	20.6	44.4	23.8	13.5
Year.....	22.2	101.1	24.4	173.0	24.5	251.4	24.6	358.9	23.6	850.2	25.5	953.8
Minimum.	0.0	—	0.0	—	7.0	—	8.0	—	11.2	—	12.0	—
Maximum.	41.9	—	40.5	—	47.0	—	41.1	—	33.4	—	43.8	—

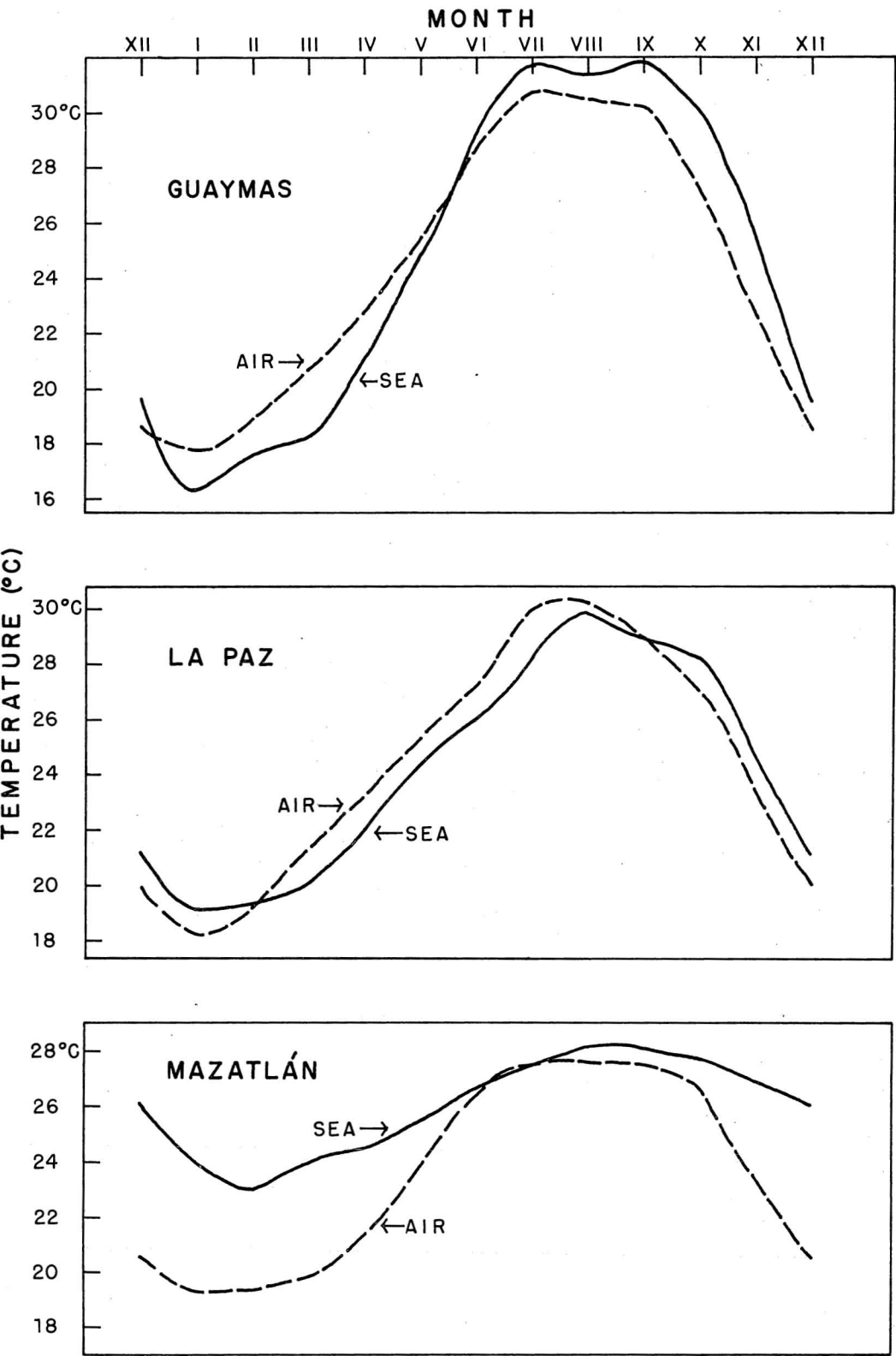


FIG. 5. Air and sea surface temperatures in Guaymas, La Paz, and Mazatlán.

the dry steppe type, and in southern Sinaloa it is tropical.

The distribution of air temperatures (Fig. 5) shows a temperature minimum in January and February and a maximum in August and September. The annual range in temperatures increases from south to north and is somewhat greater along the coast of Baja California than along Sonora and Sinaloa. The mean annual range at the entrance is around 10°C. and in the northernmost part about 20°C. The extreme annual range (Table 1) is approximately twice the average annual range (Serv. Met. Mex., Boletín Anual). In general the air is warmer than the sea during the first half of the year and cooler during the second, except for Mazatlán, where the air is always cooler than the sea (Fig. 5).

The distribution of winds (Table 2) shows that the monthly average wind velocities are

quite low, lying between 1.5 m/sec and 6.1 m/sec. The higher values are found in winter and spring. The direction of winds varies with season and with distance from the entrance. During winter, northerly winds are predominant in the entire Gulf, but in summer the southern half of the Gulf is mostly influenced by southerly winds. In the northern half, southerly winds blow only one or two months of a year.

Winter gales of short duration, locally known as chubascos, are frequent and velocities may occasionally reach 30 m/sec.

Hurricanes are not as rare in the Gulf as is generally believed. Between 1910 and 1930 thirty-nine were registered (Schott, 1935: 280). These hurricanes, known as "El Cordonazo," may enter the Gulf any time between May and November, but are most frequent in September and October (Fig. 6).

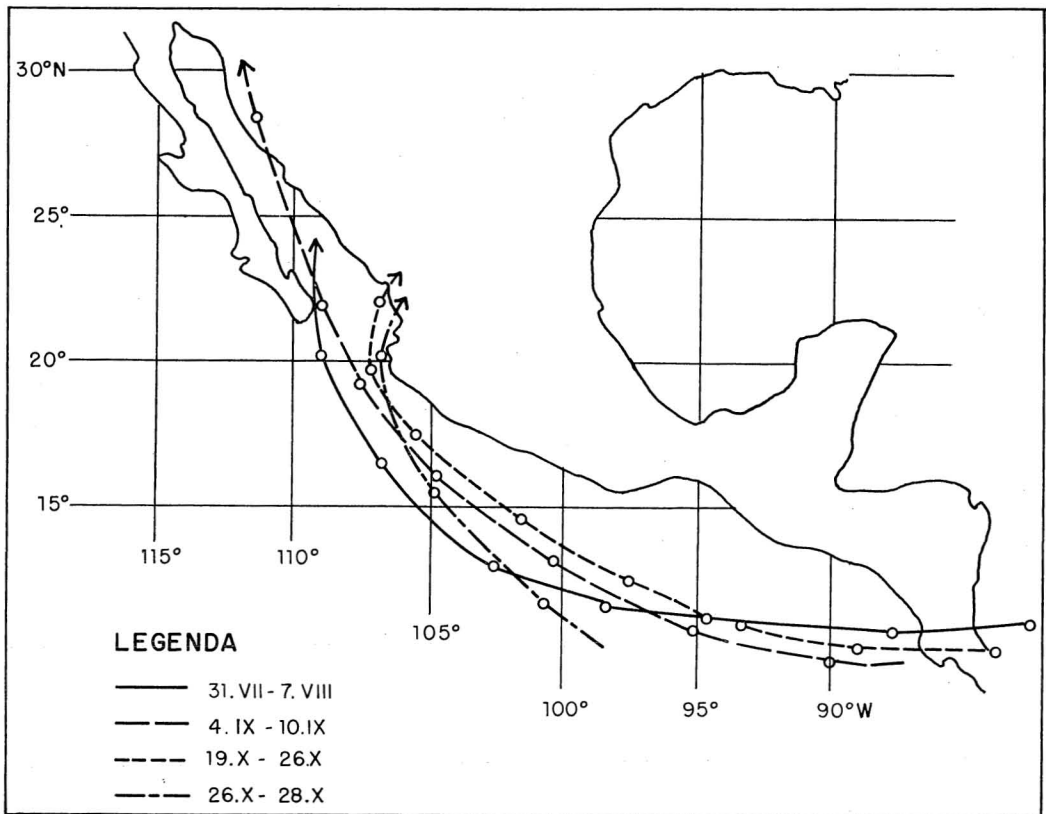


FIG. 6. Paths of hurricanes in 1936. (After Serv. Met. Mex., Boletín Anual, 1936.)

TABLE 2
MEAN MONTHLY WIND VELOCITY IN LA PAZ,
GUAYMAS, AND MAZATLÁN
(Serv. Met. Mex., Boletín Anual)

	LA PAZ	GUAYMAS	MAZATLÁN
	m/sec	m/sec	m/sec
January.....	2.6	4.8	6.1
February.....	2.4	4.2	5.9
March.....	2.2	5.3	5.5
April.....	2.3	5.1	5.0
May.....	2.1	4.6	4.8
June.....	2.4	4.3	4.6
July.....	2.0	3.5	4.3
August.....	2.0	3.6	4.9
September.....	1.5	4.4	5.0
October.....	1.8	4.8	5.1
November.....	2.3	4.6	4.1
December.....	2.3	4.9	5.5
Year.....	2.2	4.5	5.1

In La Paz winds are northerly from November until March and southerly from April until October.

In Guaymas winds are northerly from August until May and southerly in June and July only.

In Mazatlán winds are northerly from November until April and westerly from May until October.

They originate in the Caribbean Sea or off the coast of Central America and it takes them between five to seven days to reach the Gulf (Serv. Met. Mex., Boletín Anual).

If one compares the distribution of winds and the occurrence of the rainy season with the migrating low pressure system over western Mexico (Fig. 7) it is seen that northerly winds are found with the low pressure to the east, and southerly winds with the low pressure to the northwest. The beginning of the rainy season is connected with the appearance of southerly winds that carry moist air into the Gulf and give rise to uplift rain.

Evaporation is one of the most important factors in the Gulf and is responsible for the high salinity observed in the surface layers. The amount of evaporation has been determined from pan observations at a few shore stations (Serv. Met. Mex., Boletín Anual). These measurements show a main maximum in summer and a main minimum in winter. The amount of annual evaporation varies between 1800 mm. in La Paz and about 3000

mm. in Guaymas (Table 3). The values are consistent from year to year for each station and the deviations from the above values are generally less than 10 per cent (Serv. Met. Mex., Boletín Anual).

Since evaporation from pans is not strictly representative for evaporation from the sea surface, it is of interest to see how the observed evaporation from pans compares to evaporation derived from indirect methods.

The use of the energy budget method is restricted, because the advection term cannot be evaluated.

In the meteorological approach a straight line relationship between the evaporation, E , and the product of wind velocity, W , and vapor pressure difference, Δe , is assumed (Jacobs, 1951); the coefficient of proportionality depends upon the height where the wind velocity and the humidity has been measured, and upon the roughness of the sea surface. In the following the coefficient of proportionality will be taken as 4.26 (Jacobs, 1951) so that

$$E = 4.26 W \Delta e$$

where E is in mm/month, W in m/sec, and Δe is in mb.

A comparison between the pan and computed evaporation for the year 1938 is shown in Table 3, and it is readily seen that notable differences exist. The computed evaporation is less than the observed evaporation (Fig. 8) for La Paz and Mazatlán. In La Paz the maximum evaporation occurs in summer and the minimum in winter; in Mazatlán the observed evaporation shows a winter minimum and a summer maximum, whereas the computed evaporation has a summer minimum and a fall maximum. The summer minimum is due to the low wind velocities observed during this season. Values for Guaymas are not strictly comparable because the pan observations were made on a nearby station farther inland; nevertheless it is interesting to note that there the total annual amount of evaporation is considerably higher than in La Paz or Mazatlán.

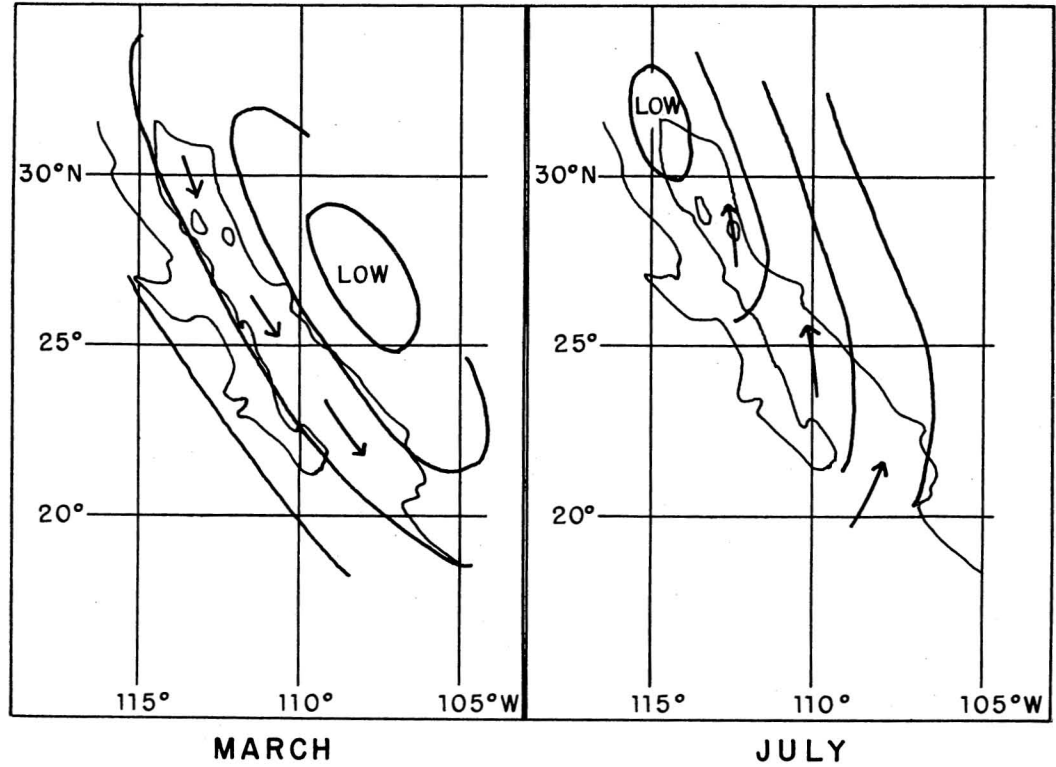


FIG. 7. Position of the low pressure in March and July, and resulting winds.

TABLE 3
MEAN MONTHLY EVAPORATION
 E_p = measured from pans, E_e = computed

	LA PAZ (1938)		GUAYMAS (1943)		MAZATLÁN (1938)	
	E_p	E_e	E_p	E_e	E_p	E_e
	mm.	mm.	mm.	mm.	mm.	mm.
January.....	139	76	139	174	185	172
February.....	120	41	206	216	213	194
March.....	129	81	286	269	148	129
April.....	119	98	351	276	205	133
May.....	146	127	446	337	210	163
June.....	166	126	420	299	211	130
July.....	174	172	294	280	230	123
August.....	197	156	246	239	289	181
September.....	150	82	198	266	202	190
October.....	159	180	162	337	210	245
November.....	158	98	148	178	162	196
December.....	154	57	92	288	140	196
Year.....	1809	1294	2958	3247	2492	2071
(E_e/E_p) year.....	0.72		(1.10)		0.83	

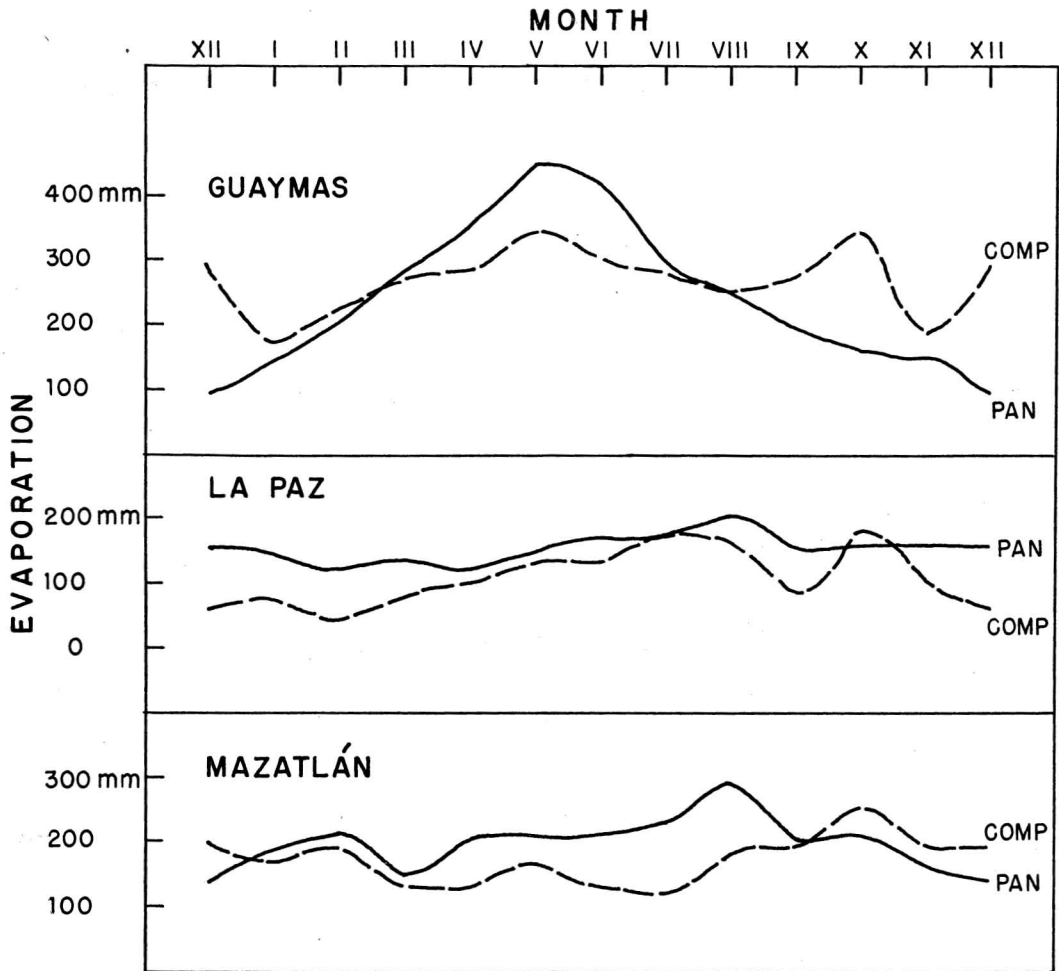


FIG. 8. Computed evaporation (E_e) and pan evaporation (E_p).

The difference, evaporation minus precipitation, has a maximum in early summer, a minimum during the rainy season, and a secondary maximum immediately after the rainy season. Except for Mazatlán during the peak of the rainy season, evaporation exceeds precipitation during all months of the year. The few available data indicate that the mean annual evaporation for the southern half of the Gulf lies between 1500 and 3000 mm. For the entire Gulf, considering the dry northern part, roughly 2500 mm. can be taken as a conservative estimate for the mean yearly evaporation. With this value the rate of evaporation

over the entire surface of the Gulf becomes $5.25 \times 10^{11} \text{ m}^3/\text{year}$ or $1.7 \times 10^4 \text{ m}^3/\text{sec}$.

GENERAL CIRCULATION

The bulk of water in and near the Gulf of California is the same as in the equatorial Pacific, slightly modified at the surface by extensive evaporation and by the admixture with water brought south by the California Current. The influence of the latter is restricted to the vicinity of Cabo San Lucas.

The great similarity between the Gulf and Pacific Equatorial water, below the thermocline, is illustrated by the close agreement

between the temperature-salinity relationships for either water mass (Fig. 9). Points for the Gulf were obtained from the "E. W. Scripps" expedition in 1939 (Sverdrup and staff, 1943). The solid curves represent the limits for typical Gulf water, the dashed curves show the limits for the equatorial Pacific (Sverdrup *et al.*, 1942: 741).

It is seen that a nearly straight line relationship exists between the points 16°C. , 35.2‰ and 9°C. , 34.6‰ . The salinity minimum lies in both cases between 34.5 and 34.6‰ and has a corresponding temperature of between 5°C. and 7°C.

The circulation in the Gulf is rather complicated and not fully understood. In winter (Fig. 10) outflow takes place at the surface and inflow at greater depths, in summer (Fig. 11) the situation is reversed. Thorade (1909) mentioned one case of oppositely running currents at the surface and at 40 m. near the coast of central Baja California.

In the northern part of the Gulf cooling of high saline water in winter leads to the formation of a bottom water mass (Sverdrup, 1941), which is characterized by a temperature above 10°C. and a salinity above 34.9‰ and a relatively high oxygen content. This water fills the isolated basins of the northern shelf

and moves southward along the coast of Baja California (Fig. 19).

Tidal currents are strong in the northern third of the Gulf and may obtain velocities of several knots in the narrows between the islands and near the mouth of Rio Colorado.

The exchange between the Gulf and the Pacific Ocean cannot be calculated accurately from the available data. It is, however, possible to get a rough estimate of the exchange of water and salt across latitude 23°N assuming conservation of these properties. If E denotes the rate of evaporation and if S_i , S_0 and Q_i , Q_0 represent the salinity and amount of the in- and outflowing water, respectively, the following equations hold (Sverdrup *et al.*, 1942: 148)

$$Q_i = \frac{S_0}{S_0 - S_i} E \quad Q_0 = \frac{S_i}{S_0 - S_i} E.$$

Taking E as $1.7 \times 10^4 \text{ m}^3/\text{sec}$ (see above), S_i as 34.6‰ and S_0 as 35.1‰ one gets:

$$Q_i = 1.19 \times 10^6 \text{ (m}^3/\text{sec)}$$

$$Q_0 = 1.17 \times 10^6 \text{ (m}^3/\text{sec)}.$$

It is seen that evaporation plays only a negligible part in the general circulation of the Gulf, and that inflow very nearly balances outflow. If one assumes that the outflowing

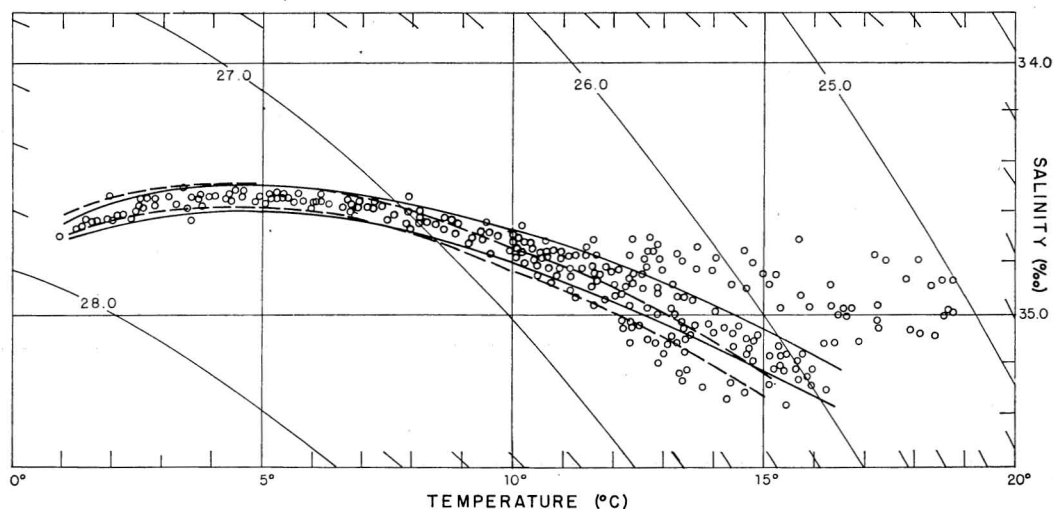


FIG. 9. Temperature-salinity diagram for the Gulf (solid lines) and for the equatorial Pacific (dashed lines).

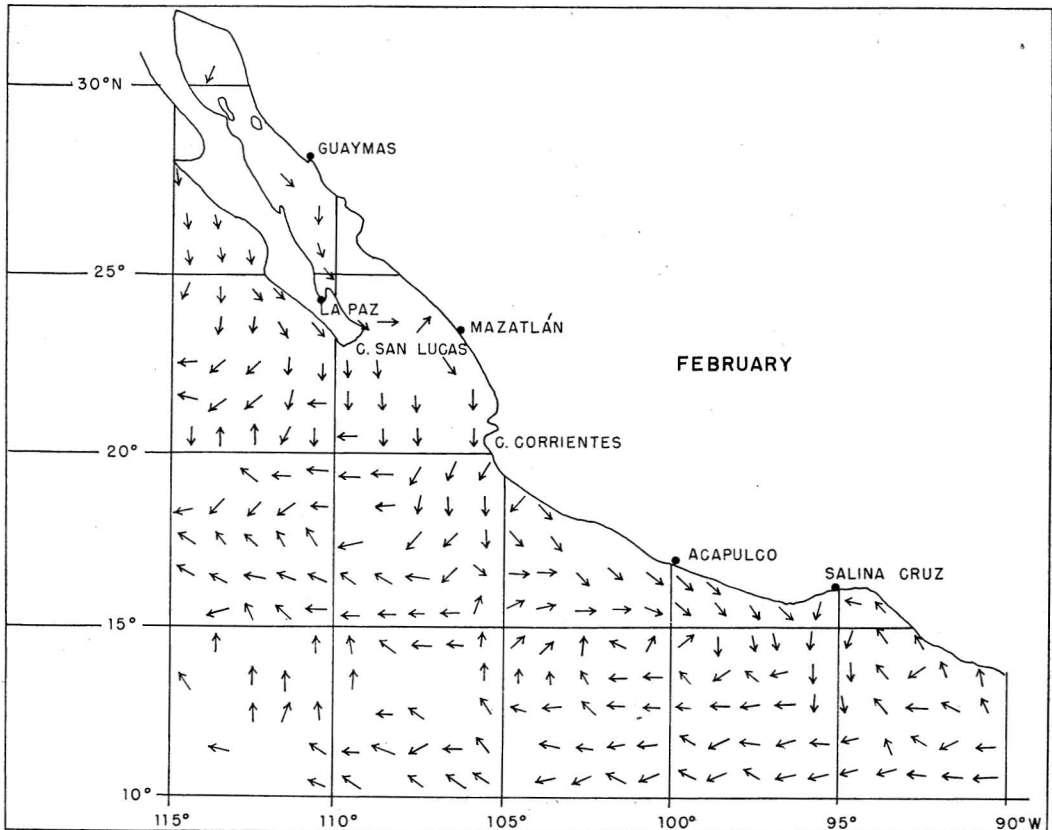


FIG. 10. Surface currents in February. (After U. S. Hydrog. Off., 1947.)

water extends over a depth range of 50 m. and inflowing over 1500 m., across latitude 23°N , the velocity of the outflowing water is 7 cm/sec and of the inflowing water 0.3 cm/sec. This calculation holds only for winter, when northerly winds are responsible for outflow at the surface.

The influence of the Gulf of California upon the adjacent Pacific Ocean is small (Sverdrup *et al.*, 1942: 732) and varies with season. The influence is greatest in winter when strong northerly winds drive the surface layers out of the Gulf and least in summer when southerly winds drive oceanic water into the Gulf. The exact distance seaward from the entrance of the Gulf that Gulf water can be detected (by its higher salinity) is not known.

The circulation in the vicinity of the Gulf of California is affected by the water carried

south by the California Current and by the water found off Mexico and Central America. The former is characterized by a low temperature, a low salinity, and a rather high oxygen content, whereas the latter has a very high temperature at the surface and a very low oxygen content below the thermocline (Sverdrup *et al.*, 1942: 730). Between both lies a transition region which, 500 miles to the west, is found approximately between latitudes 17°N and 20°N (Wooster and Cromwell, verbal communication).

In February (Fig. 10) the coastal surface circulation (U. S. Hydrog. Off., 1947) is characterized by southward currents north of about latitude 20°N and by westward flowing currents south of this latitude. An interesting feature is a large gyre off the southern coast of Mexico which is maintained by strong

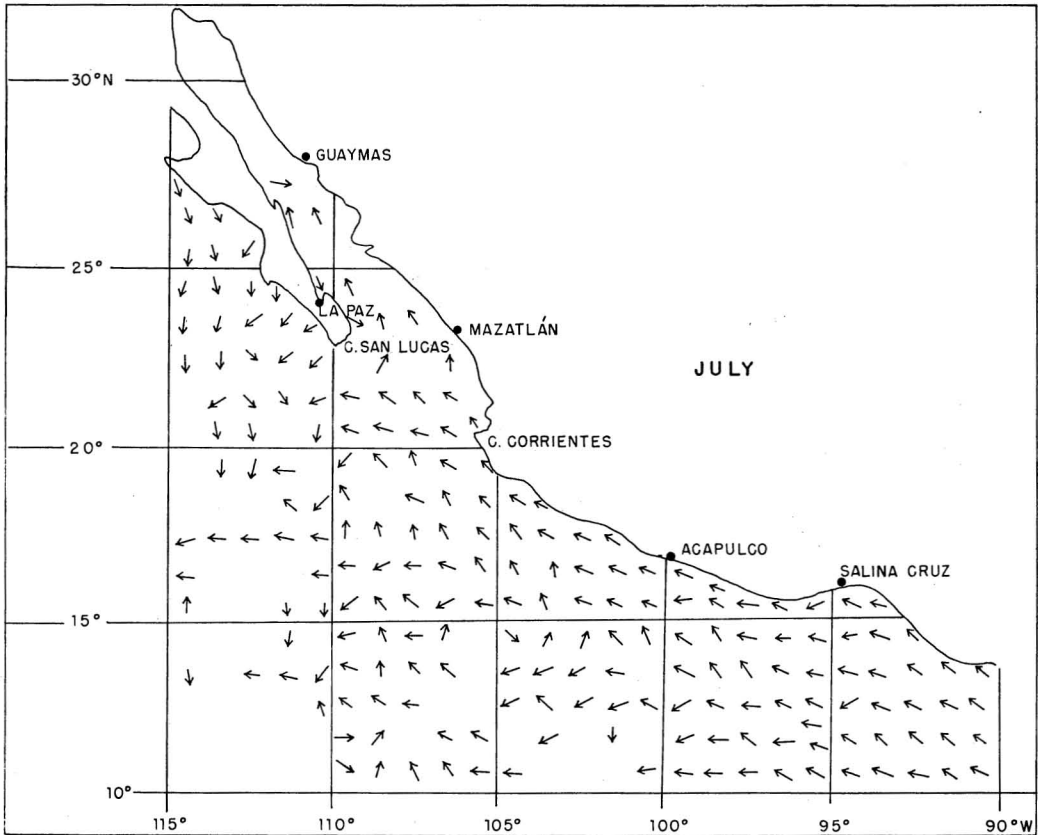


FIG. 11. Surface currents in July. (After U. S. Hydrog. Off., 1947.)

northerly winds blowing into the Gulf of Tehuantepec. This gyre is strictly a winter phenomenon and ceases as soon as the winds in the Gulf of Tehuantepec change their direction.

In July (Fig. 11) a current flows north along the coast of Mexico and enters the Gulf of California. The entire current pattern east of 110°W is characterized by a slowly west to northwest moving water mass. West of this longitude the current is toward the south north of latitude 20°N and toward the west south of this latitude.

The monthly average speeds of these currents are low and lie almost entirely within 5 cm/sec and 20 cm/sec.

FRONTS IN THE VICINITY OF THE GULF

In the following the term "front" will be

used as suggested by Cromwell and Reid (1956), i.e., as a narrow band along the sea surface across which the density changes abruptly. The terms "temperature front" and "salinity front" will be used to describe the density front, since it is only from temperature and salinity measurements that the density can be adequately determined. The definite character of a front can only be established if continuous temperature and salinity records are available. Unfortunately there are no continuous records of salinity, for which reason a description of the fronts in the vicinity of the Gulf must be based on closely spaced stations rather than upon continuous records.

Two regions of rapid temperature and salinity transition have been found to exist in the Gulf Entrance, one off Cabo San Lucas and one off Cabo Corrientes (Fig. 12). The San

Lucas transition represents a very sharp boundary between warm and high-saline Gulf water, and cool, low-saline water from the California region. It was first described by Thorade (1909), who pointed out that the intensity of the front is seasonal in character and that the maximum intensity occurs in late spring when the temperature differences between the Gulf and California Current water are greatest.

The San Lucas front is illustrated in Figure 13 (unpublished data). It is seen that the front is marked by a narrow band across which the temperature decreases from 21° to 18°C . and the salinity from 34.6 to 34.1‰ .

It is possible that when the more saline Gulf water is cooled rapidly some sinking of this water takes place at the front, but this

feature has not been investigated. The temperature structure below the San Lucas front is shown in Figure 14. The bathythermograph section from Cabo Corrientes to Cabo San Lucas was prepared from hourly temperature observations made aboard the U. S. vessel "Golden Bear" and led to the discovery of another front in the vicinity of Cabo Corrientes. It is seen that the temperature differences across the front increase with increasing depth. The increase could be explained as the result of decreased mixing at greater depth, but the feature needs further investigation.

Since the winds were northerly in April, 1949, when the "Golden Bear" crossed the Gulf Entrance it can be assumed that an already warmed water mass was driven out of the Gulf and pushed the cooler water north

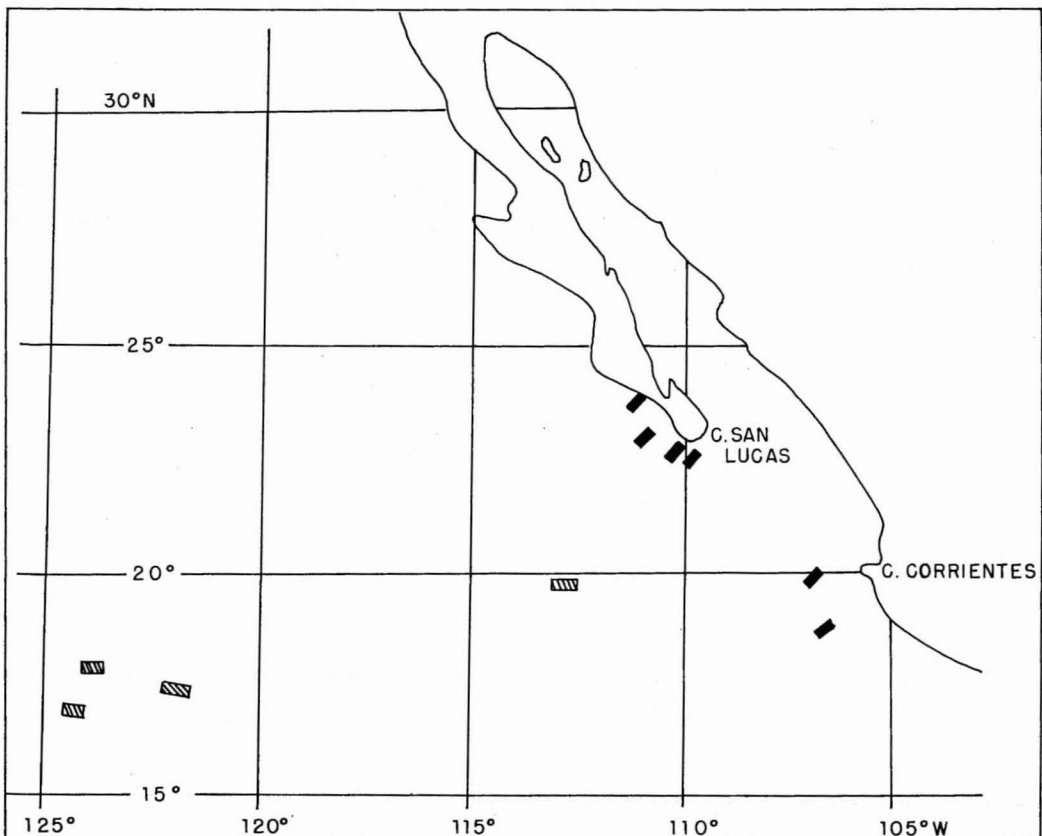


FIG. 12. Observed fronts (solid black) and transition regions (shaded) near the Gulf of California.

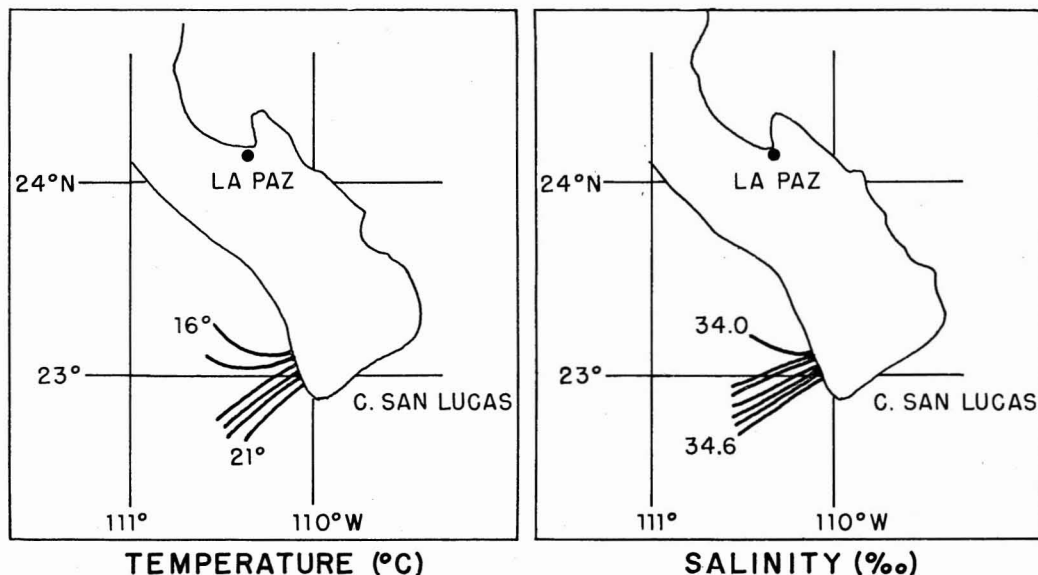


FIG. 13. Surface appearance of the San Lucas front.

of Cabo San Lucas and south of Cabo Corrientes aside, thus giving rise to the fronts observed.

UPWELLING

Upwelling in the Gulf can be expected along the east coast with northerly winds and along the west coast with southerly winds. So far only upwelling along the east coast

has been investigated (Allen, 1937).

The upwelled water is characterized by a low temperature and a low salinity when compared to the temperature and salinity of the surroundings. The surface oxygen content of the water is not necessarily a good indicator of upwelling, since it is strongly influenced by phytoplankton productivity, and by exchange with the atmosphere.

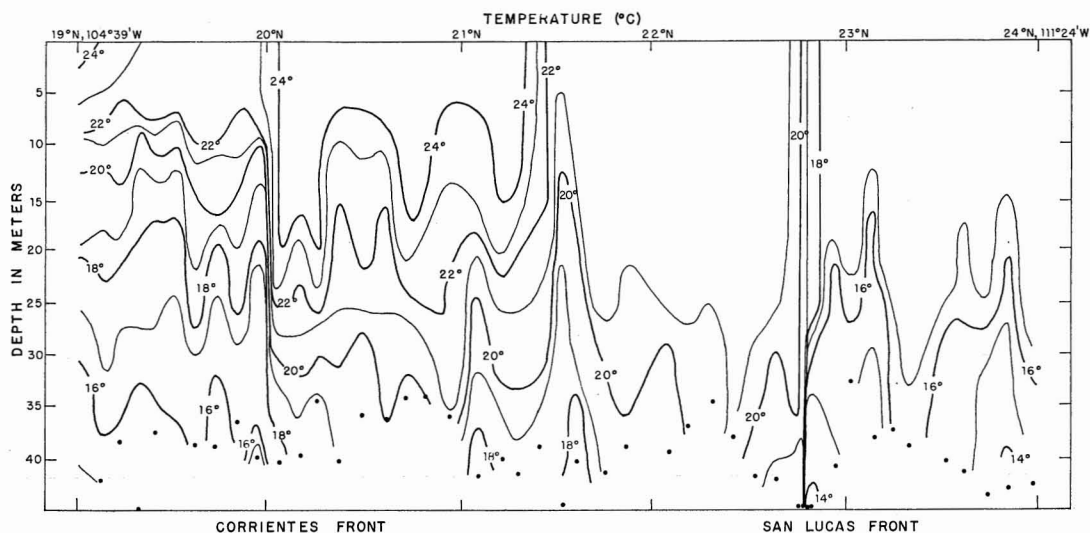


FIG. 14. Bathythermograph section from Cabo Corrientes to Cabo San Lucas, April, 1949.

Upwelling is not uniformly distributed along the east coast with northerly winds but seems rather to be confined to certain places. Such places are in the lee of Isla Tiburón, in Bahía Guaymas, in Bahía Yavaros and in the vicinity of Topolobampo (Allen, 1937). It is interesting to note that all these places are in the lee of islands or headlands, which suggests that upwelling is largely controlled by the irregularities of the coast line as well as by the winds.

Upwelling is important in the Gulf as a means of replenishing the depleted surface layers with plant nutrients from below. There are, unfortunately, no data on the concentration of plant nutrients available for the regions where upwelling occurs, and it is for the time being not possible to investigate the biological role of upwelling in a quantitative manner. The high concentration of phytoplankton in the upwelling areas in spring (Allen, 1937) is indicative, however, of a sufficient concentration in plant nutrients to support the large standing crop.

It should be pointed out that upwelling is not the only process to fertilize the surface layers with plant nutrients. Increased wind mixing and winter convection may be of equal importance. The latter process is effec-

tive in the northernmost part of the Gulf (Sverdrup, 1941) whereas the former is beneficial everywhere.

SEASONAL VARIATION OF TEMPERATURE AND SALINITY IN THE GULF

Information on the monthly variation of temperature and salinity at the sea surface in the Gulf is very scanty.

The first attempt to draw charts of monthly average sea surface temperatures was made by Thorade (1909). He collected data from ships' observations for many years and averaged them. These pre-World War I charts are still the only ones in existence (Fig. 3). Since the Second World War the U. S. Coast and Geodetic Survey has published sea surface temperatures from a few shore stations in the Gulf. These are given in Table 4. It is seen that the minimum temperatures occur in January and February and the maximum temperatures in August and September. The mean annual range lies between 23°C. and 28°C. in Mazatlán and between 16°C. and 32°C. in Guaymas. In the northern half of the Gulf the mean monthly temperatures are not known. The minimum in the northernmost part seems to be above 10°C. since this is the temperature of the bottom water found there (Sverdrup, 1941).

TABLE 4
MONTHLY VARIATION OF SEA WATER TEMPERATURE AND SALINITY FOR LA PAZ, GUAYMAS, AND MAZATLÁN
(USCGS 1951, Schott, 1935)

	LA PAZ		GUAYMAS		MAZATLÁN	
	t°C.	S‰	t°C.	S‰	t°C.	S‰
January.....	19.1	35.5	16.3	36.2	24.0	34.8
February.....	19.3	35.8	17.6	36.0	23.0	34.9
March.....	20.0	36.4	18.2	35.8	24.0	35.0
April.....	22.0	36.6	21.0	36.2	24.5	35.1
May.....	24.4	36.6	24.8	36.4	25.5	35.5
June.....	26.0	36.4	29.3	37.0	26.7	35.8
July.....	28.2	36.6	31.7	37.1	27.5	34.8
August.....	29.8	36.2	31.4	36.3	28.2	34.6
September.....	29.0	36.2	31.9	36.3	28.0	32.8
October.....	28.3	36.2	30.0	36.7	27.8	34.5
November.....	24.7	35.9	25.4	36.2	26.9	35.1
December.....	21.2	35.7	19.6	36.2	26.1	35.0
Year.....	24.3	36.2	24.8	36.3	26.0	34.9
Minimum.....	17.8	34.1	11.0	31.4	—	11.1
Maximum.....	33.3	40.4	36.2	41.0	—	36.7

The mean annual surface temperature is quite high in the Gulf and lies around 24°C. (Table 4). In Mazatlán the mean annual temperature is very high (26.0) and the surface water there is probably of advective origin, because it is always warmer than the air above it (Fig. 5).

Mean monthly salinities (USCGS 1951) are listed in Table 4. The salinity (Fig. 15) has two maxima and two minima. The first maxi-

mum is found around June and is the result of excessive evaporation. With the coming of the rainy season the salinity of the surface water falls and reaches a minimum at the peak of the rainy season. In October increasing winds and rapidly decreasing air temperatures and the lack of large precipitation give rise to a second peak in net evaporation which is also reflected in the second salinity maximum. After the October maximum the salinity de-

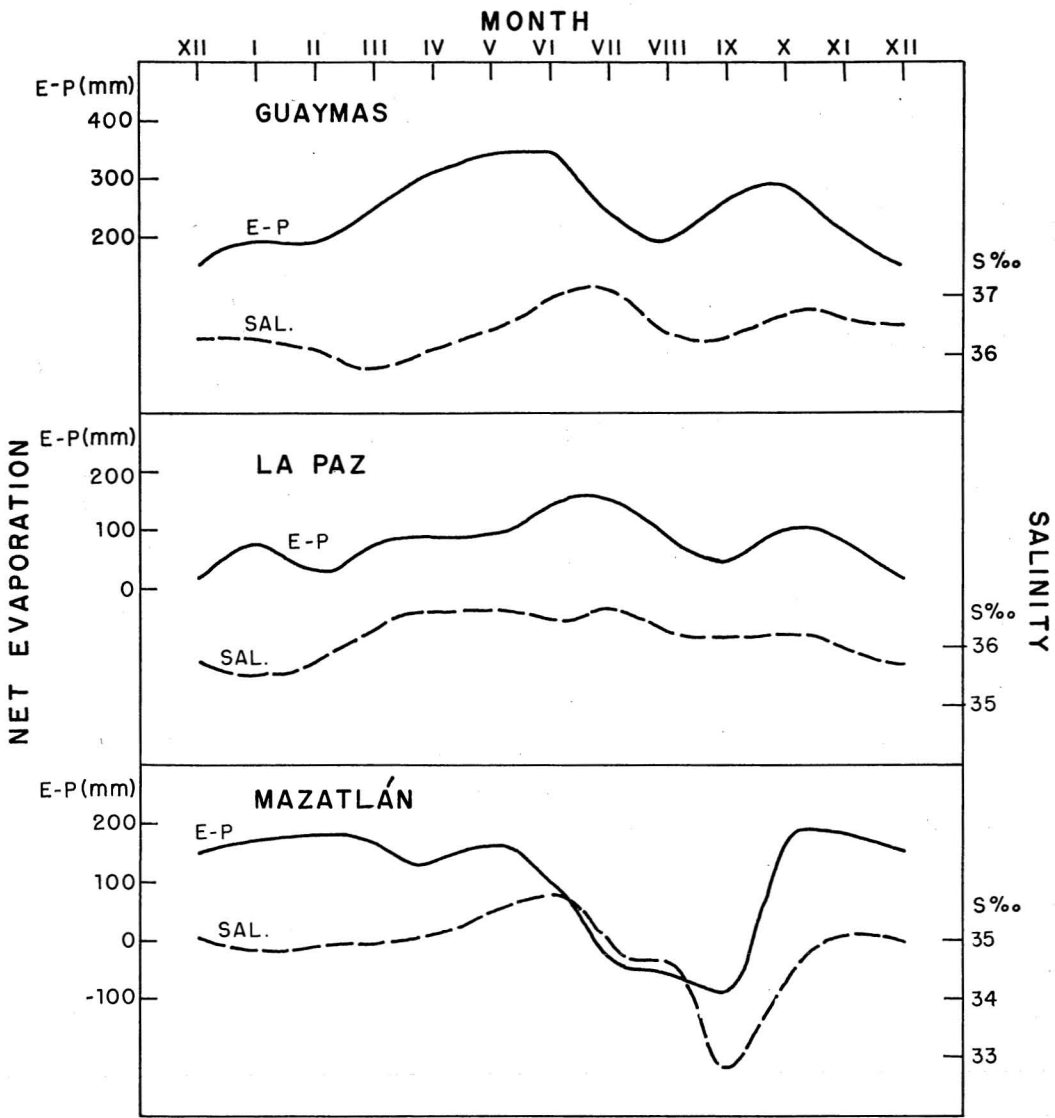


FIG. 15. Net evaporation and salinity for Guaymas, La Paz, and Mazatlán.

creases and reaches a second minimum around December. The salinity ranges between 35.5 and 36.5‰ in La Paz and between 35.8 and 37.1‰ in Guaymas. Both places are situated at the head of shallow bays where evaporation is extensive. These values are, therefore, not representative for the open Gulf.

In Mazatlán the salinity varies between 32.8 and 35.8‰. The very low value found in September (32.8‰) is possibly caused by extensive runoff from Rio Presidio during the rainy season.

Figure 15 illustrates that there is a very good agreement between net evaporation and salinity. The slight differences seen can be attributed to the different years in which the salinity was observed and for which the net evaporation was computed.

DISTRIBUTION OF PHYSICAL AND CHEMICAL PROPERTIES IN THE GULF

A preliminary discussion of the distribution of temperature, salinity, and oxygen in February and March, 1939, was published by Sverdrup (1941). A short report on the distribution of silicate and phosphate from October to December, 1940, was given by the same author (Sverdrup and staff, 1940). Here only a few conclusions will be drawn from the distribution of these properties. The distribution of phosphate and silicate in the Gulf can be discussed only qualitatively, because the measured data are such that they do not warrant a quantitative discussion.

Vertical Distribution

The Gulf can be divided vertically into a shallow upper layer (20 to 40 m. deep) where the distribution of properties is rather uniform due to wind stirring; a layer between roughly 50 and 150 m., varying with season, where the temperature, salinity and oxygen content decrease rapidly; and a deep layer, between the thermocline and the bottom, where the concentrations remain fairly constant from one season to another.

In the upper layer the concentrations vary considerably with time due to the amount of heating, cooling, stirring, evaporation, precipitation, runoff and various biological activities. Shallow and semi-enclosed bays show greater variations than the open Gulf. The layer of rapid density increase is generally closer to the surface during the warm season than during the cold season, but the available data are too few to give accurate depth ranges. Below the layer of rapid density increase the temperature decreases more or less slowly toward the bottom, but in a few deep basins, below 2000 m., a slight increase is observed due to the adiabatic effect.

The salinity shows a minimum (34.48–34.54‰) between 600 and 800 m. and increases slightly toward the bottom.

The amount of dissolved oxygen has a very pronounced minimum (less than 0.1 ml/l) between 300 and 700 m. and increases again toward the bottom.

The silicate content increases with depth and equals about 160 $\mu\text{g-at/l}$ in the central part of the Gulf where the bottom deposits are largely diatomaceous oozes.

Horizontal Distribution

The horizontal distributions of temperature, salinity and oxygen in February and March, 1939, are illustrated in Figures 16, 17, 18 and 19.

At the surface (Figs. 16 and 17) the distribution of these properties is very complicated. The high oxygen values (more than 50 per cent supersaturated in places) are probably the result of extensive phytoplankton production. The southern half of the Gulf is slightly undersaturated with respect to oxygen. Upwelling as indicated by a low temperature (and salinity) can be seen to occur in Bahia Guaymas and Topolobampo.

At subsurface depths (Figs. 18 and 19) the two outstanding features are a tongue of warm, high saline and oxygen-rich water moving to the south along the coast of Baja California and a tongue of low saline, cool

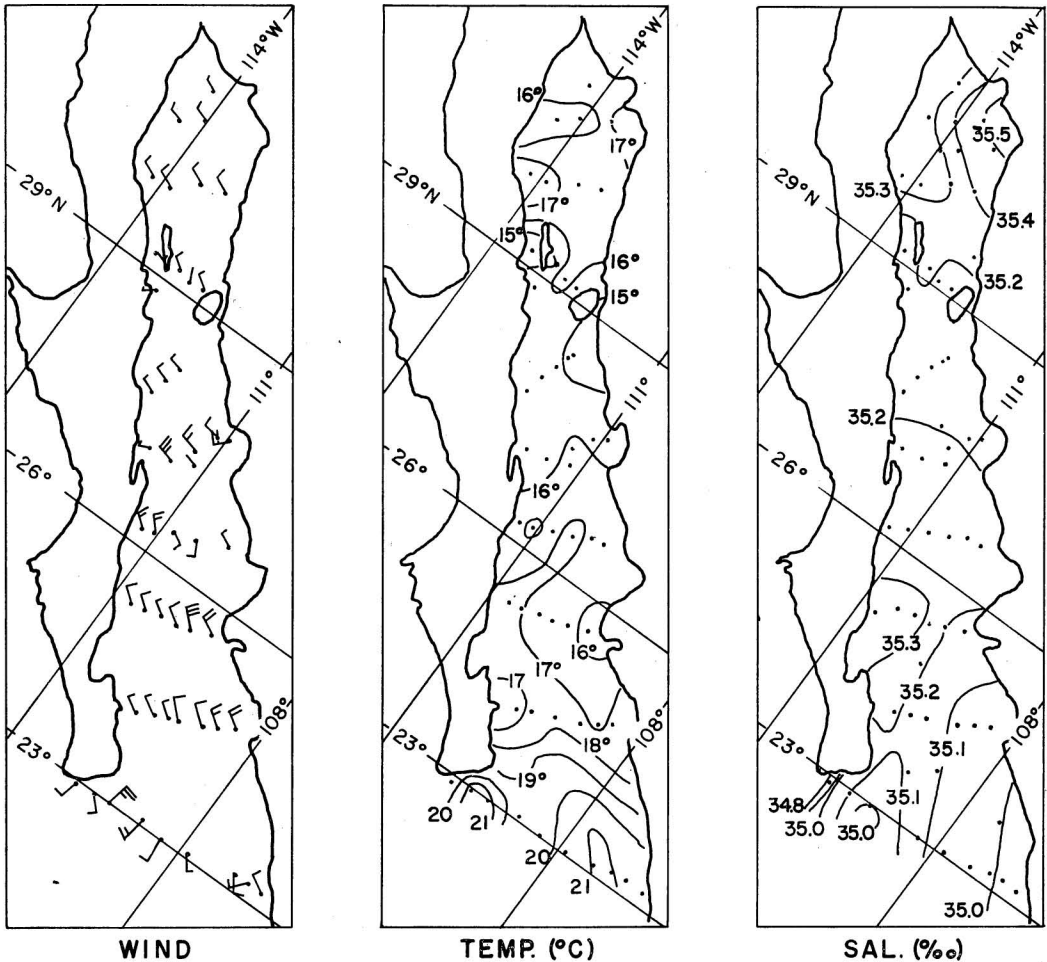


FIG. 16. Distribution of wind temperature and salinity at the sea surface in February and March, 1939.

and oxygen-poor water entering the Gulf from the south. The tongue along Baja California has possibly its origin in the northern part of the Gulf, because it is of nearly the same temperature, salinity and oxygen as the water of the northern area. The inflowing water mass shows the same characteristics as the equatorial Pacific water (Fig. 9) and represents a compensation flow to replace the water lost by evaporation and wind drift out of the Gulf.

CONCLUSIONS

The Gulf of California remains oceanographically unknown to a great extent. The results that have been presented here are based

on meager data and conclusions drawn from such data may have to be modified when more accurate and more complete data are available.

Conditions in the Gulf are dependent upon the conditions in the atmosphere and any changes that take place in the atmosphere will also be reflected in the Gulf. The submarine topography and the orientation of the shoreline also influence the circulation and hence the distribution of properties.

The bulk of the water found in the Gulf shows properties very similar to the Pacific Equatorial water mass. This water mass upon entering the Gulf is modified at the surface by extensive evaporation which increases its

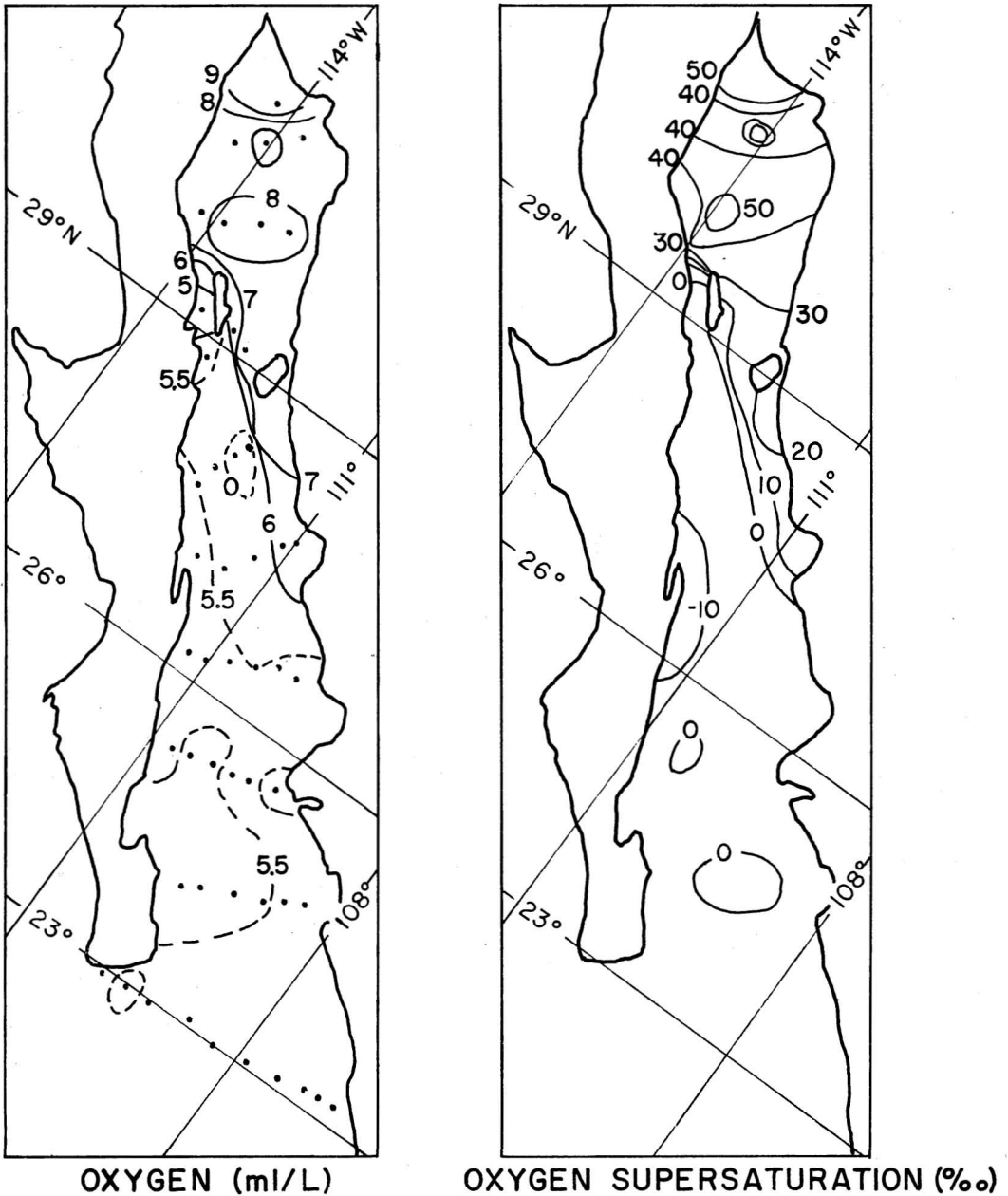


FIG. 17. Distribution of oxygen and oxygen saturation anomaly at the sea surface, in February and March, 1939.

salinity. The effect of evaporation increases as one proceeds toward the northwest.

The circulation in the surface layers is predominantly wind driven. Since the winds transport water of different origin towards the

entrance of the Gulf, it is a transition region marked by the existence of fronts of which the San Lucas front is the best developed and best known.

In the Gulf, as elsewhere, upwelling, sink-

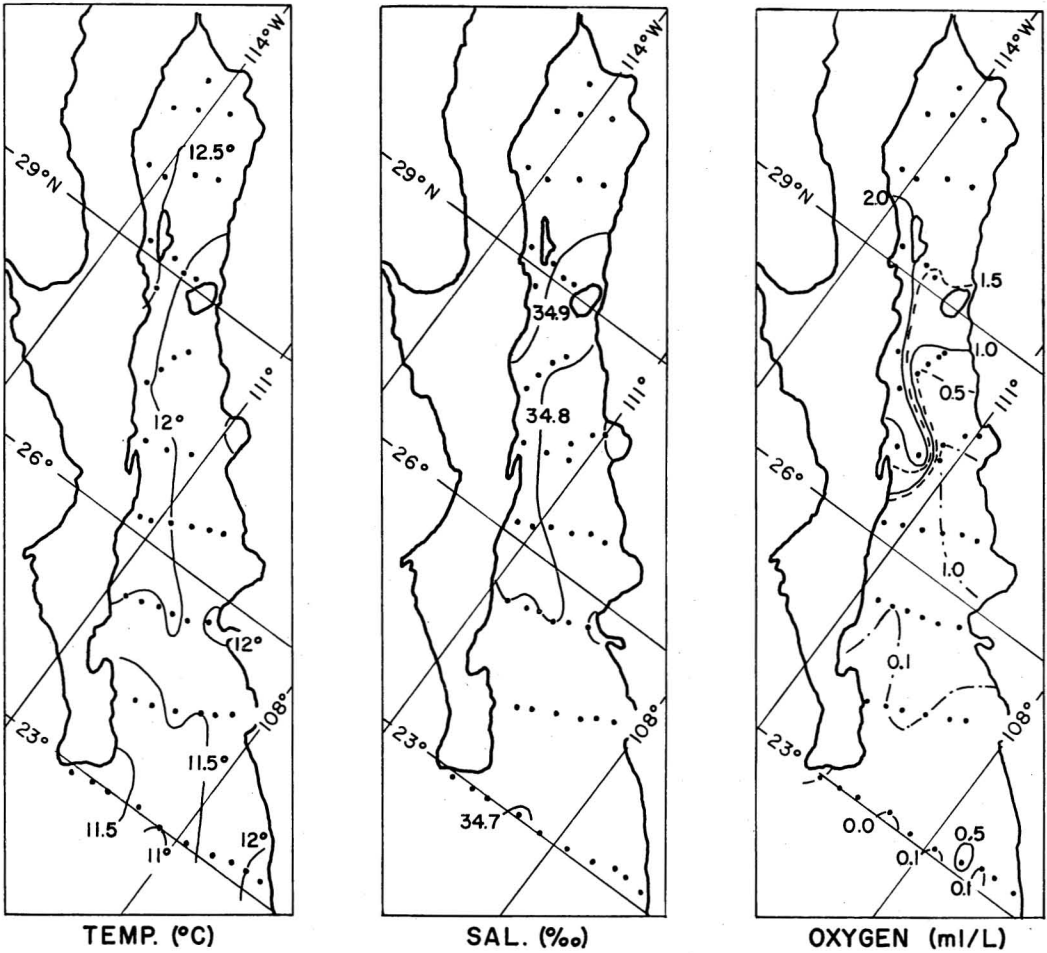


FIG. 18. Distribution of temperature, salinity, and oxygen at 200 m., in February and March, 1939.

ing, and convective overturn play important parts in determining the fertility of any given place. Convection is especially conspicuous north of Isla Tiburón and is responsible for the different hydrographic conditions there. Upwelling is largely found in the lee of headlands and islands, along the eastern coast with northerly winds, and along the western coast with southerly winds. Away from the shores the Gulf is fertile only in spring after considerable winter mixing has brought an adequate supply of phosphates and silicates to the surface. During the rest of the year the surface waters are relatively barren.

The field for investigations in the Gulf is

nearly unlimited and it is the hope of the author that in the future increasing efforts will be directed towards the scientific exploration of one of the most fascinating seas in the Pacific, the Gulf of California.

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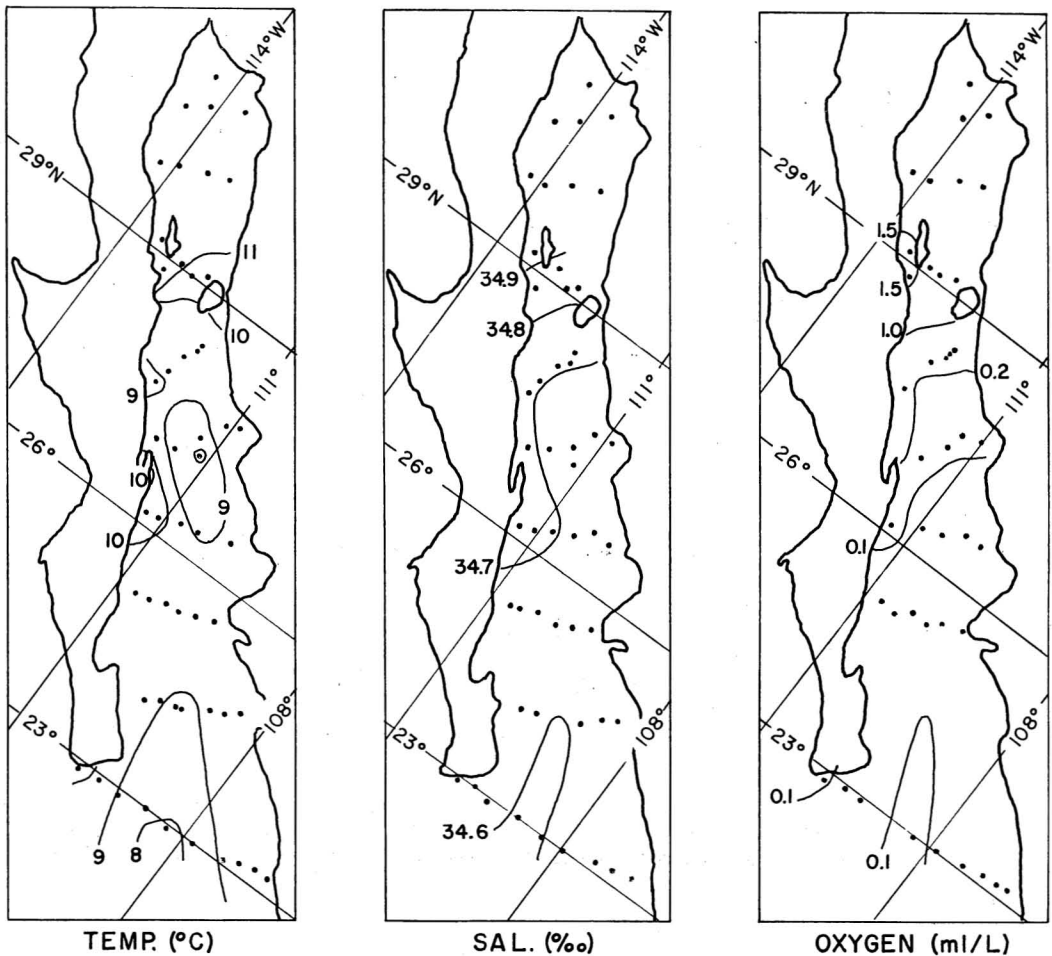


FIG. 19. Distribution of temperature, salinity, and oxygen at 400 m., in February and March, 1939.

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